

Light and Electromagnetic Waves Teaching in Engineering Education

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Suggestion of physics laboratory exercises and discussion of the physics laboratory curricula for engineering majors where the properties of light and electromagnetic waves are studied in parallel. It is shown that one of the important educational advantages of an experimental study of the properties of microwaves as an example of electromagnetic waves simultaneously with the properties of light are, on one hand, visualization of the properties of microwaves, and on the other hand, provide evidences that light is an electromagnetic wave.

I. INTRODUCTION

Engineering is the application of mathematics and science to develop useful products or technologies. In other words, engineering is turning ideas into reality. Physics is the study of the physical world and physics is an indispensable component in engineering curricula because technology is based on our knowledge of physical laws. Physics remains the leader of the modern natural sciences, the theoretical basis of modern engineering and as no any other science, promotes the development of creative and critical thinking in future engineers. Good training in physics also provides a solid base for lifelong learning.

Research in education in different countries shows that students at the college and even university levels continue to hold fundamental misunderstandings of the world around them. Science learning remains within the classroom context and just a small percentage of students are able to use the knowledge gained at school for solving various problems of the larger physical world^{1,2}.

In most of the courses students hear lectures without strong connections to their everyday experiences. Students usually do not have the opportunity to form their own ideas, they rarely get a chance to work in a way where they are engaged in discovery and building and testing models to explain the world around them, like the scientists do.

In the last four years I started to include some ‘simple’ conceptual questions in the exams of the physics courses I taught. The results were at first quite surprising: Most students performed very poorly on the conceptual questions which most physics would consider as to be almost ‘too easy’, while they sometimes solved ‘difficult’ multiple-step quantitative problems better. Some of the ‘top’ students with high scores on the quantitative problems had very low scores on the conceptual part³. One of the questions which I asked is “What are the similarities and differences between electromagnetic waves and light? The best short answer I had was “Light is an electromagnetic wave” without any deeper explanation of the properties and phenomena. I had a lot of speculations about light but only a few students mentioned that light

is the part of the electromagnetic spectrum the human eye can detect and they listed the main properties of electromagnetic waves. This motivated me to revise physics laboratory curricula and develop physics laboratory exercises where the properties of light and electromagnetic waves are studied in parallel. Indeed, one of the places where active and collaborative learning can be realized is the physics laboratory, where students become active participants of the learning process^{4,5,6,7}.

When Maxwell showed that electric and magnetic fields can propagate through space according to the classical wave equation and found the equation for the speed of propagation of electromagnetic field to be

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}, \quad (1)$$

where ϵ_0 and μ_0 are electric permittivity and magnetic permeability of free space, he evaluated the numerical value for the speed of these electromagnetic waves by substituting the numerical values for ϵ_0 and μ_0 and obtained the remarkable result: m/s⁸. Maxwell recognized that this result is very close to the experimentally measured speed of light and made a great conceptual conclusion that light is electromagnetic waves. Of course, this conclusion does not surprise physicists today. Equation (1) is one of the great equations in physics stemming as it does from Maxwell’s electromagnetic theory. This equation unifies three seemingly disparate fields of physics: electricity, magnetism and optics.

Since electromagnetic wave concepts are usually unfamiliar, abstract, and difficult to visualize, conceptual analogies from familiar light phenomena are invaluable for teaching. Such analogies emphasize the understanding of continuity of electromagnetic waves and support the spiral development of student understanding. We found that the approach of teaching the topics of electromagnetic waves and optics in parallel in the physics laboratory is very helpful and useful.

The following experiments can be easily designed and they provide a methodical introduction to electromagnetic theory using microwave radiation and light: the study of the inverse square law of the dependence of the

intensity of radiation (microwave and light) on the distance, the law of reflection and refraction, investigation of the phenomenon of polarization and how a polarizer can be used to alter the polarization of microwave radiation and light, studying interference by performing the double-slit experiment for microwave radiation and light. Finally students measure the wavelength of laser light and microwave radiation using the corresponding versions of the Michelson's interferometer, and recognize that these two forms of radiations differ only by the wavelength or frequency.

To perform the above mentioned experiments we are using a regular light source or He-Ne laser for optics, and microwaves transmitter and receiver for microwave electromagnetic radiation experiments. Today for experiments with microwaves PASCO⁹, as well as DAEDALON¹⁰ provide excellent sets. In our laboratory we are using PASCO equipment. We are using the same design for light and microwave experiments to demonstrate the similarity of measurements and the only difference is that in the case of light experiments students can see the phenomena and measure its physical properties and in the case of the microwaves they can observe the same phenomena through the meters reading of the intensity of the microwave radiation.

The purpose of the present paper is to introduce laboratory curricula for the study of the properties of light and microwaves in parallel in the general physics laboratory course for engineering majors, especially for electrical engineering and telecommunication students. The article is organized as follows: Sec. II introduces the experiments for the inverse square law of the dependence of the intensity of light and microwave radiation on the distance from a source of electromagnetic waves, in Sec. III we analyze and discuss the reflection and refraction experiments for microwaves and light, the double-slit interference and polarization experiments for light and microwaves are discussed in Sec. IV and Sec. V, respectively. Interferometer measurements for wavelength of light and microwaves are presented in Sec. VI, and conclusions follow in Sec. VII.

II. INVERSE SQUARE LAW FOR LIGHT AND MICROWAVE RADIATION

The intensity received from the pointlike source of an electromagnetic wave is inversely proportional to the square of the distance from the wave source and an inverse square law can be written in the form

$$I = \frac{L}{4\pi r^2}, \quad (2)$$

where L is the luminosity of the source. To observe this phenomenon we designed the experiment where the photoelectric photometer has been used to measure the intensity of light in increments of distances from the light

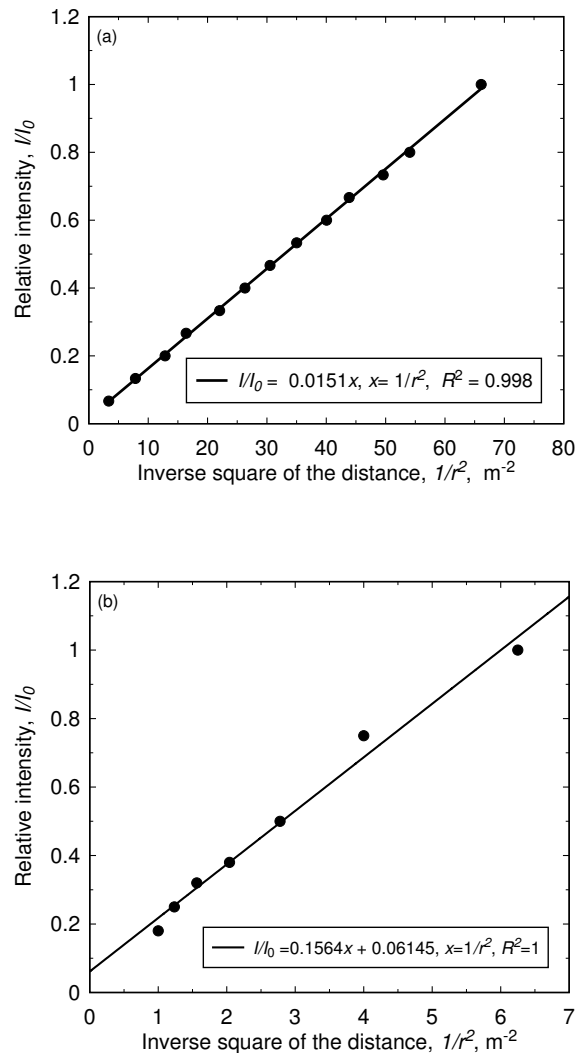


FIG. 1: Inverse square law for light (a) and microwaves (b).

source. In the case when the students perform the measurements for the intensity of electromagnetic waves by using the microwave transmitter and receiver they gradually increase the distance between the transmitter and receiver by moving the receiver. Students represent the results of the measurements for the dependence of intensity on the distance for light as well as for microwaves in graphical form by plotting the relative intensity versus the inverse square of the distance as shown in Figs. 1a and 1b. The analysis of these graphs shows that intensities of visible light as well as invisible microwaves decrease inversely proportional to the square of the distance from the source.

III. REFLECTION AND REFRACTION OF LIGHT AND MICROWAVES.

There are two fundamental laws of geometric optics: the law of reflection and Snell's law – the law of refraction. Today's laboratory class technology allows students to verify these laws using a beam of light as well as a beam of monochromatic laser light. Students can perform experiments for the reflection and refraction of light gradually changing the angle of incidence and measuring the angle of reflection or the angle of refraction and at the same time visually observing the propagation of the incident ray and reflected or refracted rays for each of the incident angles. By plotting the graph of dependence of the angle of reflection versus the angle of incidence they can find that the slope of this graph is unity and therefore, conclude that the angle of incidence equals the angle of reflection. In the same way by plotting the graph of the sine of the angle of incidence versus the sine of the angle of refraction students see that there is a linear dependence and from the slope of the graph determine the index of refraction for the given medium. Fig. 2a represents an example of such dependence for refraction of light in glass. We are suggesting studying reflection and refraction of microwaves in parallel with these optics experiments. The difference of the setting for these experiments is that in the case of light students actually see the reflected and the refracted rays, but in the case of microwaves the reflected and refracted electromagnetic waves are invisible and students determine the angle of refraction as well as the angle of refraction of microwaves by finding the maximum intensity for the reflected or refracted microwave radiation. Using a transmitter and receiver of microwaves and a metallic reflected plate and gradually increasing the angle of incidence, students can find the angle of refraction which corresponds to the maximum intensity of reflecting microwaves. In the case of refraction the incident microwaves are refracted on the prism mold filled with styrene pellets. The angle of the refracted microwaves can be found by the maximum intensity meter reading of the refracted waves. Plotting the same graphs as in the case of light experiments for the angle of incidence versus the angle of reflection and for the sine of the angle of incidence versus sine of the angle of refraction, students can verify the laws of reflection and refraction for the microwaves and justify that these are the same as for light. Fig. 2b presents the results for these kinds of measurements for reflection of the microwaves.

IV. DOUBLE-SLIT INTERFERENCE FOR LIGHT AND MICROWAVES

The other experiment in optics which is easy to visualize is double-slit interference for light. This is the standard set which is available on the market. Performing this experiment students can see a clear interference

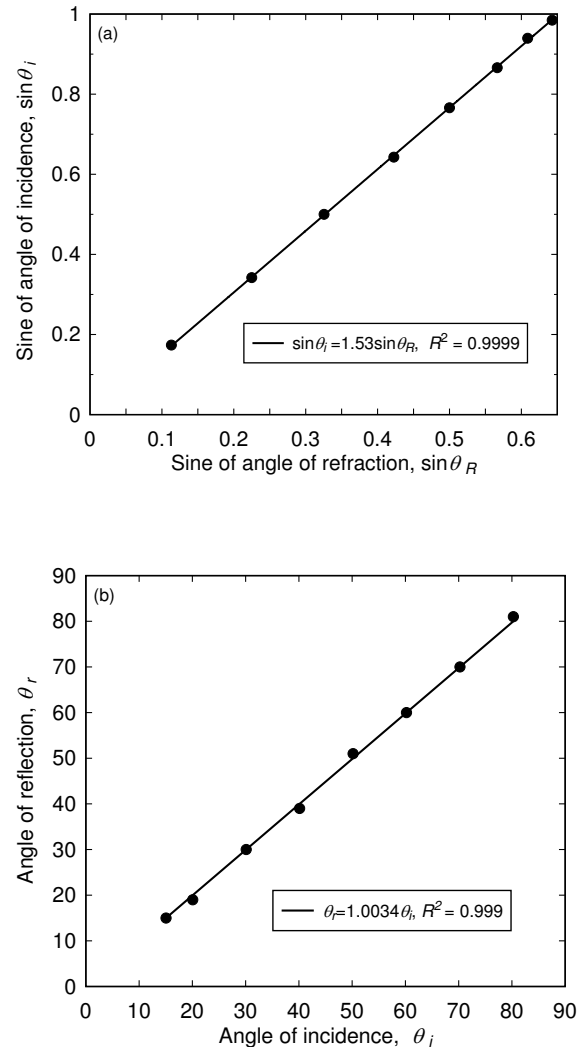


FIG. 2: (a) Refraction of light in glass. Dependence of the sine of the angle of refraction on the sine of the angle of incidence. (b) Reflection of microwaves. Dependence of the angle of reflection on the angle of incidence.

pattern. Of course, there are many different experiments, which also demonstrate the interference of light and visualize the interference concept for light. We are choosing the double-slit interference of light because a somewhat similar phenomenon occurs when microwaves pass through a two-slit aperture and can be easily set and performed with microwaves. When incident microwaves from a transmitter radiate on a double-slit aperture, the intensity of the microwave beyond the aperture will vary depending on the angle of detection by a receiver. For two thin slits separated by a distance d , maxima of the

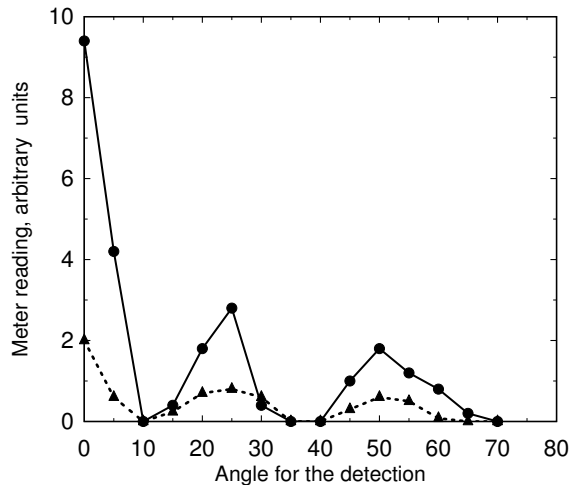


FIG. 3: Interference pattern for microwaves.

intensity will be found at such angles that

$$d \sin \theta = m\lambda, \quad (3)$$

where θ is the angle of detection, λ is the wavelength of the incident radiation, and m is any integer. Gradually changing the angle by 5° for the detection position of the receiver the student measures the intensity of microwaves beyond the double-slit aperture. Fig. 3 presents an example of such measurements for two different runs. The solid curve represents the measurements when the receiver is positioned close to the double-slit aperture, while the dotted curve corresponds to the measurements when the distance between the receiver and double-slit is increased. To analyze the results of the experiment students for the given wavelength of microwave calculate the angles at which they would expect the maxima and minima to occur and compare with the locations of observed maxima and minima.

V. POLARIZATION PHENOMENA FOR LIGHT AND MICROWAVES

The other laboratory activities which excite students and catch their attention deal with observation of polarization of light. Two activities which are the easiest to set in the undergraduate college physics laboratory are polarization by absorption and polarization by reflection. As it is well known when unpolarized light is incident on a polarizing material, the transmitted light is linearly polarized in the direction parallel to the transmission axis of the polarizer. When two polarizing materials are placed

in succession in a beam of light, the first is called the polarizer and the second - the analyzer, the amount of the light transmitted by the analyzer depends on the angle θ between its transmission axis and the direction of the axis of the polarizer. The intensity of light transmitted by both polarizer and analyzer will be given by Malus's law

$$I = I_0 \cos^2 \theta, \quad (4)$$

where I_0 is the intensity of the light incident on the analyzer. The standard setting for this experiment requires the light source (regular light source for qualitative observation or laser for a quantitative observation), polarizer and analyzer to be placed in succession in a beam of light and screen or photometer for measurement of the intensity of transmitted light. Students set up a polarizer-analyzer system and the laser light source as shown in Fig. 4 and orient and align their polarization axes. Slowly rotate the analyzer in either direction while observing the intensities of the light spot on the screen. Their observation shows that intensity of light changes. Afterwards, students attach the analyzer to the special component carrier of the angular translator connected to the photometer with the fiber probe and place it instead of the screen. A student starts at $\theta = 0^\circ$ and rotates the analyzer by increasing the angle in 10° increments up to 180° and measures the intensity of transmitted light for the different angles of polarization. The typical results of the measurements are presented in graphical form as shown in Fig. 5a. Then students study the polarization phenomenon for microwave radiation. The microwave radiation from the transmitter is already linearly polarized along the transmitter diode axis. Therefore, as the microwave propagate through space, its electric field remains aligned with the axis of the diode. Thus, if the transmitter diode was aligned vertically, the electric field of the transmitted wave would be vertically polarized. If the detector diode of the receiver is at an angle θ to the transmitter diode, the receiver would only detect the component of the incident electric field that was aligned along its axis. Students rotate the initially aligned receiver from 0° to 180° in increments of ten degrees and measure the intensities of the microwave. Plotting the graph for the relative intensities versus the angle students can observe the similarity with the polarization of light. By comparing the data in Figs 5a and 5b and plotting the graph of the relative intensity versus as shown in Fig. 6 student can conclude that the intensity of polarized light as well as polarized microwaves follows Malus's law.

To better understand the mechanism of polarization for the experiment with microwaves, student places a grid of parallel conducting strips under different angles between the transmitter and aligned receiver and again measures the intensities for the different angular positions of the grid. Linearly polarized microwaves are sent through a grid of parallel conducting strips. We choose

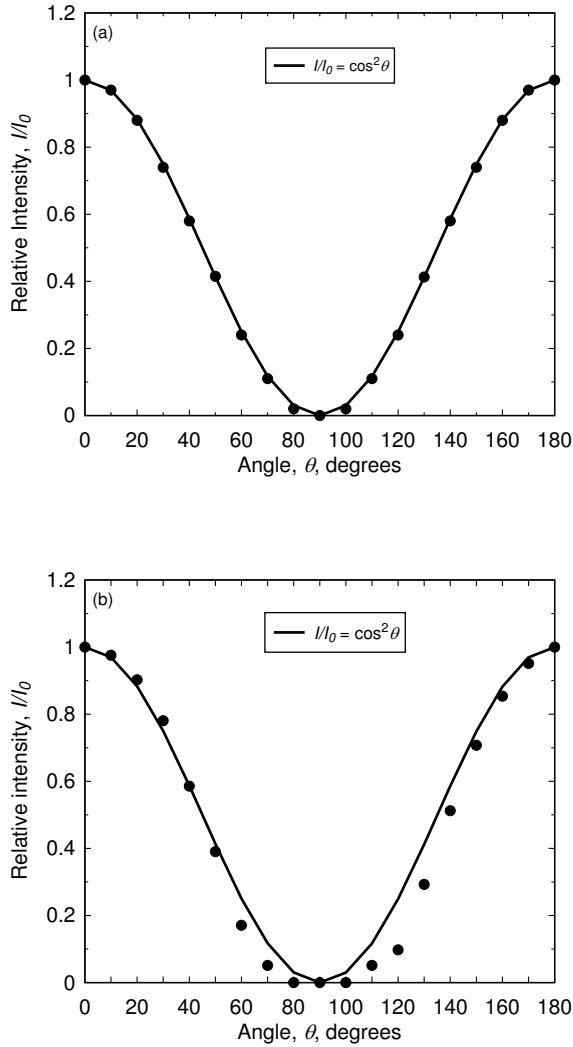


FIG. 4: Dependence of the relative intensity of the polarized light (a) and microwaves (b) on the polarization angle.

the two perpendicular directions used to represent the linearly polarized incident beam to be parallel and perpendicular to the metallic strips. The polarized waves with electric field vector parallel to the conducting strips are absorbed by the strips. The oscillatory field parallel to the strips transfers energy to the electrons that can move along the strips; it is the polarization direction perpendicular to the strips that is transmitted. So the metallic strip grid acts as a polarizer, a device for producing polarized microwaves. The axis of a polarizer is the direction parallel and antiparallel to the plane of polarization of the transmitted waves. The axis of a polarizer is not a unique line but simply a direction or a whole collection of lines oriented parallel to each other. There-

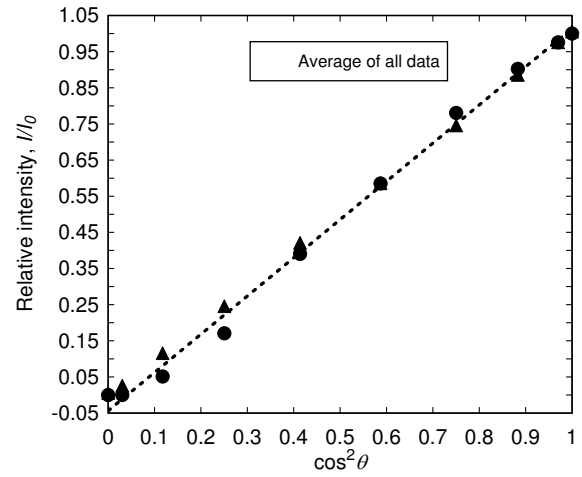


FIG. 5: Relative intensity for polarized light and microwaves versus $\cos^2 \theta$. Triangles represent experimental data for light and circles — for microwaves.

fore, for the metallic strip grid polarizer of microwaves, the axis of the polarizer is a direction in the plane of the polarizer perpendicular to the direction of the strips. Thus, the experiments of polarization of light and microwaves are complementary which helps to understand and visualize the phenomenon and mechanism of polarization.

Hence, on one hand students visualize the phenomenon of polarization by observing the polarization of light. They can observe that by changing the angle between the polarizer and analyzer the brightness of the spot of light changes from maximum bright to dark when the angle is changing from 0° to 90° . On the other hand, polarization of microwaves helps to visualize the mechanism of polarization by observing that intensity changes depending on the angular position of the grid.

VI. INTERFEROMETER MEASUREMENTS FOR WAVELENGTH OF LIGHT AND MICROWAVES

In the interferometry technique we superpose (interfere) two or more electromagnetic waves, which creates an output wave different from the input waves. Because interference is a very general phenomenon with waves, interferometry can be applied to a wide variety of electromagnetic waves, including optical spectrum and microwave, and can be used for measurements of wavelength of light as well as microwaves. The Michelson interferometer is the most common configuration for optical interferometry and can be very easily adapted for microwave

interferometry. In many scientific and industrial uses of interferometers, a light source of a known wavelength is used to measure incredibly small displacements - about 10^{-6} meters. However, if you know the distance of mirror movement, you can use the interferometer to measure the wavelength of a light source as well as a source of other electromagnetic waves. The aim of this experiment is to make the students familiar with the simplest type of interferometers and use the interferometer to measure the wavelength of a helium-neon laser light source and a microwave source. The first part of the experiment is centered at giving the students a "feeling" for the sensitivity of a Michelson interferometer and the different types of interference patterns which can be observed visually with the laser source. The Michelson interferometer produces interference fringes by splitting a beam of monochromatic laser light by a partially transparent reflector so that one beam strikes a fixed mirror and the other a movable mirror. When the reflected beams are brought back together, an interference pattern results. By measuring the distance d_m , that the movable mirror moved toward the beam-splitter and the corresponding number of fringes m , students are able to determine with high precision the wavelength of the laser light as

$$\lambda = \frac{2d_m}{m} \quad (5)$$

The advantage of this part of the experiment is that the students visually see the interference pattern. This presents a way of direct understanding of important concepts in wave optics. In the second part of this experiment students use the Michelson interferometer that is setup with a microwave transmitter, partial reflector, two metallic reflectors and receiver. Microwaves travel from the transmitter to the receiver over two different paths. In one path, the microwave passes directly through the partial reflector, reflects back to the first reflector, and then is reflected from the partial reflector into the receiver. In the other path, the microwave reflects from the partial reflector into the second reflector, and then back through the partial reflector into the receiver. If in the optical part of this experiment student can visually observe these pathways, for microwaves the paths are invisible. Now by moving one of the reflectors the student changes the path length of one wave, thereby changing its phase at the receiver. While watching the meter, and slowly moving the reflector, students can observe relative maxima and minima of the meter deflections. By measuring the reflector's displacement distances and corresponding numbers of maximum relative intensity the wavelength of microwave radiation can be determined using the same Eq. (3) as for visible laser light.

The other advantage of this experiment is that students learn and understand why Michelson's interferometer has become a widely used instrument for measuring extremely small distances by using the wavelength of a known light source. Based on this experiment students

understand that resolution for measurement of distances depends on the wavelength of electromagnetic radiation and why an optical interferometer (an interferometer using visible light rather than microwaves) provides better resolution when measuring distance than a microwave interferometer.

The detailed procedures of some experiments discussed in this article are presented in Refs.[11] and [12]. Some of the experiments are computer-based and some are performed in the traditional way. Because not every lab has computer access, computer-assisted experiments serve as supplements to the traditional experiments. This allows instructors to find the appropriate balance between traditional and computer-based experiments for teaching topics of light and electromagnetic waves in the physics laboratory.

VII. CONCLUSION

Our ultimate goal is to improve engineering major students' learning and motivation in physics courses by presenting the abstract material in the traditional curriculum through real-time experiments in a laboratory session. This approach assumes the experimental study of the properties of light and microwaves in parallel. One of the important educational advantages of the simultaneous study of electromagnetic waves and light is to show that light and electromagnetic radiation have the same properties so that the students can visualize the properties of the electromagnetic radiation through observation of light propagation. In other words, the abstract invisible properties of microwaves are visualized via observing visible properties of light. On the other hand, the observation of the polarization of microwaves helps to visualize and understand the mechanism of the polarization of light. It is important to underline that all this is real-time visualization but not computer-based animations, simulations or interactive multimedia design cases. In our approach we suggested studying the properties of electromagnetic microwave radiation and light in parallel by performing the same laboratory experiments for light and microwaves to show that these two phenomena demonstrate the same properties and follow the same laws. By performing these experiments students become active participants of the learning process.

The other advantage in teaching light and microwaves in parallel is that students realize that for measuring the same properties of electromagnetic waves of different range of the electromagnetic spectrum you should use different equipment and different precision of measurements. In our approach by analyzing data for the same phenomenon through two different methods of measurements, students gain a greater understanding of the concepts behind the experiments.

The visualization of complex phenomena does not by itself reach our goal. We put this visualization into a context of the same invisible phenomena and created a

series of parallel activities that involve questions to motivate the students and investigations of practical devices.

Acknowledgments

This work is supported by US Department of Education under the Grant P120A060052.

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